THE HAILSTORM OF APRIL 1938 AT WASHINGTON, D. C.

UNUSUAL FALL OF LARGE HAILSTONES AT WASHINGTON, D. C.

By GILES SLOCUM

[Weather Bureau, Washington, D. C., May 1938]

On April 29, 1938, Washington and its vicinity were visited by a destructive hailstorm. Damage was estimated at $100,000. At the Weather Bureau, two windows were broken, several automobile tops punctured, and leaves and twigs stripped off trees.

The storm approached the Weather Bureau office from the west at about 12:15 p. m., E. S. T., with rain beginning about 12:30 p. m. The rainfall soon became heavy and a few hailstones were seen mixed with the rain. Then larger stones, unaccompanied by noticeable rain, commenced to fall at about 12:36, with the wind becoming strong for a few seconds.

After the storm, some of the hailstones were picked up and in the majority of cases found to be roughly hemispherical at one end and conical at the other, the longest axis passing through the vertex of the cone—the shape for maximum streamlining. Figures 1 and 2 show some of the stones gathered after they had partially melted. In both photographs, the stones are shown approximately in natural size. The circle in the center of figure 2, for comparison, is the size of a pile of quarter dollars. The largest stones measured at the Weather Bureau were somewhat less than an inch and a half in their longest dimension, but some the size of baseballs, according to reports, fell in northeast and southeast sections of the city and at Bolling Field airport.

Falls of damaging hail in Washington are rare, and if the report of stones as large as baseballs in outlying portions of the city is authentic, this ranks among the heaviest hailstorms Washington has ever experienced.

THE FORMATION OF IRREGULARLY SHAPED HAILSTONES

By DAVID L. ARENBERG

[Blue Hill Observatory, Milton, Mass., August 1938]

On April 29, 1938, the city of Washington and its suburbs were treated to a display of hail that surpassed previous records in that locality. Not only because of the financial losses estimated at $100,000 to greenhouses, automobiles, crops, and buildings, but because of the unusual shape of the icy missiles, the occasion merits attention. As the storm occurred during the annual meeting of the Meteorological Section of the American Geophysical Union, meteorologists were not lacking to examine the effects.

There were two distinct periods of hail. Rain which began to pour from a thunderstorm that had built up in the northwest at 12:30 p. m., changed to hail at 12:32, to rain 2 minutes later, and back to hail at 12:36 which lasted until 12:54. In the first stage the stones were few and small, about an eighth of an inch across, displaying no concentric shells, and were irregularly shaped like kernels of corn.

The second period was more severe and caused all the destruction, with hailstones whitening the ground and piling up a few inches deep in gutters and depressions. A size of three-fourths inch was common and many hailstones were measured over an inch in length. The majority were triangular pyramids with distinct faces and dihedral angles of various sizes and spherical bases. Quadrilateral, pentagonal, and other polygonal forms were also frequent; so that, in general, the shape was that of kernels of corn, although much larger and with structural features additional to those of the first type. The shorter axis varied from about two-thirds to one-third that of the longer which was along the altitude of the pyramids. The outer layers were very rough, consisting of loose ice particles and crystals, and rime, that soon melted disclosing the hard interior. The interior consisted of three portions: One of hard, clear ice extending from the apex to about one-fourth the distance to the base; the second containing as many as 12 circular arcs of varying thickness of alternating clear and opaque ice easily visible to the naked eye for one-third the total length, with centers of curvature concentric at the apex; the third portion was of white ice of irregular formation of no definite structure and softer than the previous two.

The method of formation of such irregularly shaped hailstones has been variously explained. One of these is that, from an initial irregularity of the core, the development continued unsymmetrically; the flattened base being kept continually against the droplet bearing air currents, so that streamline flow determined the resultant shape of the added water as it froze. The hypothesis has various difficulties in the present case although it serves for less marked irregularities: (1) The apparently complete absence of any spherical stones would require a uniform condition of asymmetry at the start; (2) streamlining of a partly frozen nucleus into a teardrop design would be most apt to develop a circular or elliptical cross section rather than the polygonal one observed in the trailing apex; (3) the successive layers of clear ice built up around the hailstone would have to be complete, due to excess liquid flowing from face to rear—instead, the portions of arcs found were sharply truncated; and (4) the streamlines about an irregularly shaped object are very seldom circular or concentric with a point on the surface, in contradiction to the condition observed above.

Hann[1] in publishing some photographs of hailstones, which, with the exception that the number of layers were not so numerous, are very similar to those that fell in Washington, briefly remarks that they have the appearance of being formed by the explosion of balls of ice, and other observers believed collisions in the upper air may have shattered the stones, but no further details are given.

The following preliminary computations indicate that the above process is within the realm of possibility.

The rate of heat loss may first be determined from the formula for the steady state conduction of a sphere of radius R_2 with surface temperature fixed at T_2, and whose temperature at a distance R_1 from the center is maintained at T_1.

$$dH=4\pi k\frac{(T_1-T_2)}{R_2-R_1}R_1R_2dt \tag{1}$$

This loss will freeze completely a layer of the nucleus PLM grams where P is the percentage of the liquid nucleus by weight that is frozen, L the latent heat of fusion, M the total mass may be determined from the volume of the shell $4\pi R_1^2$ in area and dR_1 thick.

$$4\pi k(T_1-T_2)\frac{R_1R_2}{R_1-R_2}dt=PLM, \qquad M=4\pi R_1^2dR_1 \tag{2}$$

$$t=\frac{PL}{k(T_1-T_2)R_2}\int(R_2-R_1)R_1dR_1 \tag{3}$$

[1] Hann-Süring: Lehrbuch der Meteorologie, 4 Ed. Leipzig, 1926, p. 720.

In a specific instance, the time required for the nucleus to freeze solid may be determined by substituting the following reasonable values: L is roughly 80 cal/gm; k, the conductivity for solid ice, is 0.0044 cal/cm/sec; T_1 is 0° C. and T_2 may be taken at —15° C. for a dry atmosphere; P as 10 percent; R_1 as 2 cm.; and R_2 as 4 cm.

$$(4)\quad t=\frac{PL}{k(T_1-T_2)R_2}\left[\frac{R_2R_1^2}{2}-\frac{R_1^3}{3}\right]_0^2$$

$$=\frac{0.10\times 80}{0.0044\times 15\times 4}\left[\frac{4\times 2^2}{2}-\frac{2^3}{3}\right]=162 \text{ seconds.}$$

It seems that with the additional knowledge concerning the process of hail formation given by recent authors, notably Schumann,[2] the suggestion of Hann's can be expanded into a complete analysis of the structure of such stones.

In accordance with the usually accepted idea of the origin of hail, the stone started from a rounded nucleus of either compacted, partially melted snow or a large raindrop in which freezing had already begun and formed a network of spicules throughout. Here the latter type may be considered preferable as there would then be no occluded air bubbles. This core could readily grow to a size of one-fourth inch radius, the size of the clear apex portion of the hailstones, through the accretion of supercooled droplets. Assuming the proper proportions between the solids and liquids, the spherical form could be maintained through turbulent air friction and surface tension. Winds, even in excess of the classical terminal velocity of $8m/s$ for raindrops would not disrupt it.

Since the solid crystals would prevent convection, the outer layer would freeze completely first. As long as supercooled droplets were being deposited at a rate sufficient to cover the stone with a film of water, the stone's temperature would remain at 0° C. throughout. Further growth would take place at the surface, as Schumann has described, by the conduction of heat and evaporation of water to the surrounding colder air. The interior would remain in equilibrium because there would be no further transfer of heat across the surface to freeze the liquid remaining within. Because of the slight lowering of the freezing point of water with increasing pressure, the freezing point within the center would be slightly lower than on the free surface. Layer upon layer of clear and opaque ice could be added until the diameter of the stone reached the required 1½ to 2 inch. Should the hail be carried to such a height that all external liquids would be frozen, a temperature of below 0° C. could eventually penetrate to the nucleus.[3] As the nucleus began to freeze, the change of state would produce a change in volume capable of creating a tremendous internal pressure. This could easily exceed the breaking strength of the ice shell and the hailstone would explode like an aerial bomb, shattering into polygonal pyramids with spherical bases.

This time is the minimum amount since the conditions for the steady state demanded for equation 1 were not observed in equation 3. As the pressure within the hailstone may reach the bursting point long before the freezing is completed even 162 seconds may be unnecessarily long.

Whether the hailstone will explode or merely expand is difficult to determine since it is known that above —9° C. ice is sufficiently plastic to flow and offset the internal pressure developed, and also since accurate measurements of the tensile strength, modulus of elasticity, and compressibility of ice are extremely variable and difficult to make at the lower temperatures.[4]

Since water expands one-tenth its volume on freezing, the nucleus considered here will change its volume by one one-hundredth. Assuming no plastic flow and negligible compression, the outer radius will be increased by an amount

$$(5)\qquad dR_2=\frac{\frac{4}{3}\pi R^3_1}{4\pi R^2_2}1/100=\frac{8}{300\times 16}=0.00166 \text{ cm.}$$

Let us consider the stress developed in the outer layers to be equal to that required to produce a proportional extension in a uniform bar of solid ice. Then Hooke's law gives

$$(6)\qquad s=\left(\frac{dR_2}{R_2}\right)E=\frac{0.00166}{4}\times 3\times 10^7 g/cm^2$$

$$=1.24\times 10^4 g/cm^2=1.22\times 10^7 \text{ dynes/cm}^2$$

where E is Young's modulus and is an approximate value.[5]

Since the tensile strength of ice is from 1 to 10 times 10^3g/cm^2, failure would readily occur.

If any "bombs" were capable of withstanding the internal forces, it is hardly likely they could survive the impact with the ground because of their unstable condition. In the cases where the nuclear liquid was small, the parts might not be completely severed and would refreeze in a malformed shape upon the release of pressure. On extremely mild occasions, or where air bubbles were occluded, the expansion would merely produce the radial structure often seen.[6]

In the remaining time of descent, ice and rime could be added over the fragments. Portions of the nucleus would become completely frozen and hard, in contrast to the usual condition of intact spherical stones which have soft nuclei indicative of incomplete freezing.

If it were possible for a raindrop to remain liquid at the center while a frozen layer formed over the surface, or if the crystal-liquid mixture were not firmly frozen to the shell, the resulting fracture might produce the lens or saucer shaped hail occasionally seen.

The above discussion of the formation of irregularly shaped pyramidal hailstones such as fell in Washington on April 29, 1938, leads to the following conclusions: Due to certain internal structural features of the stones, the previously held hypothesis that such forms developed from the maintenance of an initial irregularity of the nucleus has been discarded. A suggestion due to Hann that the stones arose through the bursting of a much larger spherical stone has been found to explain the structure and also to satisfy certain mathematical requirements and is therefore advanced as being more valid.

Finally I should like to thank Dr. C. F. Brooks and Dr. A. F. Spilhaus for their interest and criticism of this paper while it was still in a formative state and for suggesting several important additions.

[2] T. E. W. Schumann: The Theory of Hail Formation. *Quar. Jour. R. M. S.* v. 64, p. 3, Jan., 1938.

[3] Hann. (p. 722) states that the temperature of hailstones measured immediately after their fall is often much below zero and can reach from −5 to −15° C.

[4] H. T. Barnes: *Ice Engineering*, Renouf Publ. Co., Montreal 1928. See pp. 21–59 for a consideration of the properties of ice.

[5] Ewing, Crary, and Thorne in an article published in *Physics* 8: 1–9, June 1934 make the following statement: "The values of Young's modulus and Poisson's ratio for ice are found to be 9.17×10^{10} dynes/cm² and 0.365, respectively, in the range −5° to −15° C.".

[6] F. W. Very: The Hailstorm of May 20, 1892, *Amer. Met. Jour.*, pp. 263-273, Oct. 1893. This author gives a description and cuts of the internal structure of hailstones whose nuclei he concludes froze from the surface inward.

NOTE ON THE HAILSTONES OF AUGUST 9, 1938, AT WILLIAMSTOWN

The following description of hailstones that fell in Williamstown, Mass, on August 9, 1938, has been received from Prof. Willis I. Milham who gathered the reports from several reliable observers:

> Four forms (of hailstones) are mentioned—a perfect sphere; a flattened sphere; entirely irregular; pyramidal with a curved base. The commonest seems to have been the pyramidal form and many comment that the pyramids were long and sharp. The flattened sphere comes next. Some remark that two or three stones were often welded together long before they reached the surface and fell as a solid mass. They were laminated, and one observer remarked that they looked like mothballs surrounded by clear ice. There was almost no thunder and lightning in Williamstown. In Pownal, Vt., about 5 miles away, where the storm was even more destructive, there was more lightning and thunder.

THE STRUCTURE OF HAILSTONES

R. P. Johnson, of the Research Laboratory, General Electric Co., Schenectady, N. Y., in an account of the broken hailstones, published in Nature, vol. 142, page 172, July 23, 1938, states that the shapes of these stones and their stratification showed plainly that they were fragments of larger spherical stones about 30 mm in diameter, in which clear and cloudy layers had alternated about every 2 mm. It was concluded that where fracture took place it was at a high level, for the pieces, which ranged up to 15 mm in size, appeared to have terminal velocities suited to their sizes. They did not break on striking the pavement. The absence of layers of clear and cloudy ice built on to each fragment seemed to prove that the stones were fractured below the region where they were formed. The remarkable fact that all the stones were broken at the place of observation, while 2 miles away only complete stones fell, suggested to J. Schremp (another of the research engineers of the General Electric Co.) that the shattering was caused by a pressure wave that was set up by a bolt of lightning that passed near to them as they fell.

RAINS IN KANSAS

By ANDREW D. ROBB

[Weather Bureau, Topeka, Kans., March 1938]

The interest Kansas has in rains is due at times to the lack of rain, at times to the overabundance of rain, and at other times it is due to those million-dollar rains that come to the State.

The average annual amount of rainfall varies from about 43 inches in the southeastern part of Kansas to approximately 16 inches in the central counties of the western third. The amounts of rainfall, however, are only a part of the story, for the number and magnitude of the rains are important factors for consideration in many enterprises. For example, rainfall in the counties of the central third of western Kansas is only 37 percent of that of southeastern Kansas while the average number of rains is nearly 60 percent. As data on monthly and annual amounts of precipitation are readily available in the monthly and annual Climatological Data for Kansas the discussion here will deal mostly with the number and magnitude of rains that fall over Kansas.

The term "rains" as used here means the amounts of water measured at the observation, whether from rain, snow, sleet, or hail. Each of the three Weather Bureau divisions of the State were subdivided into three districts. Three cooperative stations in each district were selected, considering geographical distribution and continuity of record. The time covered is the 40 years from January 1896 to December 1935. The limits of the magnitudes chosen for this study are as follows: 0.01 to 0.25 inch; 0.26 to 0.50 inch; 0.51 to 0.75 inch; 0.76 to 1.00 inch; 1.01 to 1.50 inches; 1.51 to 2.00 inches; 2.01 to 3.00 inches; 3.01 inches and over.

The number of rains of these various magnitudes were counted by months during this 40-year period for each of the three stations of the nine districts. The rains of like magnitudes of the three stations of each district were then averaged together to determine the average for the district. The results are summarized in tables 1 to 9.

AVERAGE NUMBER OF DAYS WITH RAIN—40 YEARS, 1896–1935

TABLE 1.—*Northwest section—Dresden, Colby, Atwood, St. Francis*

Magnitude	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Total
0.01–0.25	83	123	142	166	209	202	160	152	115	100	79	103	1,634
0.26–0.50	9	21	24	50	58	57	47	57	31	30	20	14	418
0.51–0.75	1	6	9	23	26	32	20	31	18	13	9	6	194
0.76–1.00	-----	1	3	16	13	21	16	16	14	6	4	2	112
1.01–1.50	1	1	4	11	15	16	14	13	9	6	1	2	93
1.51–2.00	0	0	1	5	6	6	6	7	4	2	1	-----	38
2.01–3.00	0	0	1	2	1	2	4	3	2	2	1	0	18
3.01 and over	0	0	0	0	-----	-----	3	0	1	2	0	0	6
Total	94	152	184	273	328	336	270	279	194	161	115	127	2,513

TABLE 2.—*North-Central section—Phillipsburg, Hanover, Beloit, Burr Oak, Alton*

Magnitude	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Total
0.01–0.25	97	116	140	175	209	211	163	163	152	120	103	104	1,753
0.26–0.50	16	28	32	57	72	69	50	52	43	44	28	18	509
0.51–0.75	7	8	13	28	36	44	27	32	22	13	12	7	249
0.76–1.00	1	5	4	16	26	21	14	18	14	11	5	5	140
1.01–1.50	0	1	4	12	18	24	17	20	12	11	5	2	126
1.51 2.00	0	1	1	3	8	10	11	9	9	6	3	1	62
2.01–3.00	0	-----	-----	2	3	4	7	6	4	3	1	0	30
3.01 and over	0	0	0	1	2	1	1	2	2	1	-----	0	10
Total	121	159	194	294	374	384	290	302	258	209	157	137	2,879

TABLE 3.—*Northeast section—Atchison, Manhattan, Frankfort, Centralia, Oketo*

Magnitude	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Total
0.01–0.25	131	131	153	168	197	160	137	149	129	135	105	114	1,709
0.26–0.50	24	37	41	63	73	65	55	51	63	42	35	34	583
0.51–0.75	7	16	19	35	44	49	32	33	37	27	16	10	325
0.76–1.00	3	5	7	20	31	27	21	21	25	18	9	3	190
1.01–1.50	2	5	10	17	21	28	25	27	24	14	11	1	185
1.51–2.00	0	2	3	6	14	13	8	10	12	4	5	1	78
2.01–3.00	0	0	2	3	10	10	7	11	10	2	2	1	58
3.01 and over	0	0	-----	-----	1	3	3	3	3	0	1	0	14
Total	167	196	235	312	391	355	288	305	303	242	184	164	3,142